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## GEOGRAPHY OF THE ASTEROID BELT

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Several hundred minor planets can now be classified into broadly defined C, S, M, and other compositional types. Corrections for observational selection bias show that at least 75% of the main belt asteroids are of Type C, about 15% are of Type S, and 10% of other types. The proportion of S objects drops smoothly outward through the belt with an exponential scale length of 0.4 AU. Objects of exceptional type are found throughout the main belt. At least for diameters  $>50$  km, the major types show very similar size-frequency relations.

Several Hirayama families show characteristic optical properties contrasting with the field population, and evidently originated as the collision fragments of discrete parent bodies. The Trojans seem to form a compositionally distinct population. Of a dozen Amor and Apollo objects observed, nine are S-like, one is of Type C, and two show unusual compositions.

## INTRODUCTION

Much of the fascination of minor planets lies in their population statistics, that is, the distribution of types over diameter and orbit. In the preceding paper Morrison (1978) has summarized the telescopic techniques that have been used for large numbers of asteroids, and described the classification into Types C, S, M, etc., recognizable in optical polarimetry, thermal radiometry, and UV colorimetry. The classification system is one step removed from attempts at mineralogical description as described by McCord (1978). The mineralogical description, where available, is to be much preferred over the simple classification by optical type, but only for the latter is a statistically adequate sampling available. At the University of Arizona we are beginning a seven-color survey, using broadband interference filters from 0.36 to 1.05  $\mu\text{m}$  wavelength, with hopes of obtaining mineralogically diagnostic data for a substantial fraction of the numbered asteroid population.

The first attempts at analysis of the population statistics was by Chapman *et al.* (1975), who classified 110 objects into C, S, and U (unclassifiable) types. Corrections for observational selection effects showed that the C asteroids are predominant, especially in the outer regions of the belt. Zellner and Howell (1977) carried out a similar exercise for 359 objects, incorporating Types M and E and using for the first time a large number of observations of UV color. The taxonomy has been more closely examined, and applied to data for 521 asteroids, by Howell *et al.* (1978). Most of the results discussed here are taken directly from the latter two papers. A bias-corrected analysis of the larger data set and more secure classifications of Howell *et al.* remain to be done.

## THE MAIN BELT

### *Observational Selection Effects*

Since minor planets differ in geometric albedo by at least a factor of ten, any discussion of distributions over diameter and distance must begin with statistically reliable diameters and must incorporate corrections for observational selection biases. Also, we must take care that objects of various types or distances are intercompared only for similar size ranges. Failure to observe these precautions can be perilous. For example, Chapman (1976) noted that classified S asteroids tended to fall near Kirkwood gaps, and C objects to avoid the gaps widely. The result is statistically well-established, and there are no obvious biases toward or away from the Kirkwood gaps in the compositional surveys. As shown by Zellner and Bowell (1977), however, Chapman's conclusion was only an artifact of comparing large C asteroids with small S objects, together with a genuine tendency for large objects of any type to avoid the gaps.

Diameters for about 200 asteroids are available from the polarimetric and thermal-radiometric surveys (Morrison, 1977a, 1978; Zellner *et al.*, 1977a; Gradie *et al.*, 1977). In addition we can obtain statistically useful diameter information from geometric albedos assumed according to the compositional type; Zellner and Bowell (1977) adopted albedos 0.035 for C objects, 0.12 for Type M, and 0.15 for Type S.

Corrections for observational sampling bias have been discussed by Chapman *et al.* (1975), Morrison (1977a,b), and Zellner and Bowell (1977). It is assumed that, in any region of the belt, the sampling completeness is a function of apparent magnitude only. Then bias factors are computed for each interval of magnitude and distance as the ratio of the number of objects sampled to the total number of asteroids known to be present. For each classified object at a magnitude and distance associated with bias factor  $n$ , we assume that  $n-1$  additional asteroids of identical size and type are present. The bias factors need not be monotonic functions of magnitude, and no distortions are introduced by particular attempts to observe faint objects or members of particular Hirayama families, so long as the sampling intervals are adequately chosen. Clearly the process is limited by the statistics of small numbers.

The bias correction process is also limited by the normalization sample. Figure 1 illustrates the distribution over heliocentric distance for 1978 numbered asteroids. This sample is itself heavily biased, being incomplete for objects fainter than about apparent magnitude 15.5, or diameters smaller than 12 km for inner-main belt S asteroids, 55 km for outer-main belt C objects, and ~150 km for the Trojans. For fainter asteroids we must depend upon some extrapolation of the magnitude-frequency relation, or results from the Palomar-Leiden Survey (van Houten *et al.*, 1970). Since few objects brighter than magnitude 16 were observed in the PLS, its region of overlap with the numbered population is somewhat problematical.

### *Frequency of Types*

According to the bias analysis of Zellner and Bowell, there are approximately 560 main belt asteroids with diameters  $>50$  km, of which 76% are of Type C, 15% of Type S, 5% of Type M and 3% of other types. Similar results, with a somewhat higher proportion of C objects, were obtained by Morrison (1977a,b). Large asteroids of the high-albedo varieties are genuinely quite rare. Zellner *et al.* (1977b) noted that there are apparently no more than two or three E asteroids with diameter  $>50$  km in the entire population. In their sample of 523 objects, Bowell *et al.* (1978) were able to identify no additional candidates for the Vesta type with diameter  $>25$  km. It is a remarkable result that mixed among the predominantly dark, carbonaceous population there can be a very few asteroids of quite exceptional type.

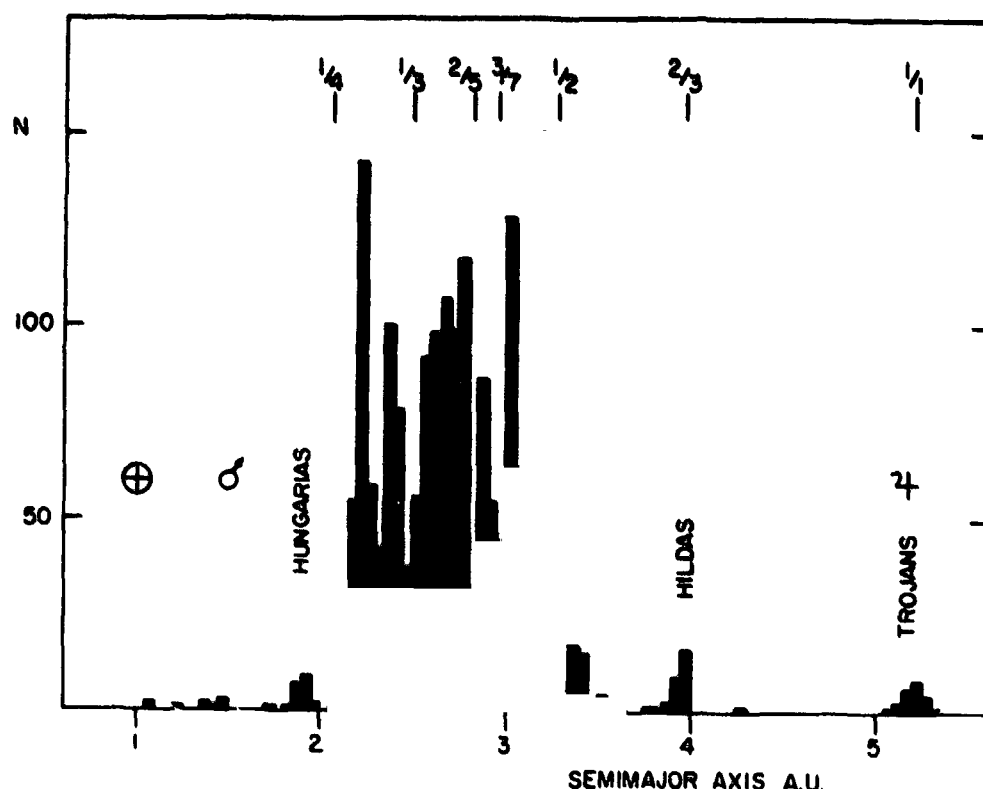


Fig. 1. Distribution over mean heliocentric distance of the first 1978 numbered asteroids, in increments of 0.05 AU. Fractions indicate the ratio of orbital periods for the principal dynamical resonances with Jupiter. Adapted from Zellner *et al.* (1977b). Data are from the TRIAD computer file (Bender *et al.*, 1978).

#### Distributions Over Heliocentric Distance

Figure 2 illustrates the general decrease of the relative frequency of S-type asteroids with increasing semimajor axis. The departures from a smooth curve are of no statistical significance, and there is no evidence for systematic differences near Kirkwood gaps. The mixing ratio drops exponentially with distance with a scale length of about 0.4 AU. Bias-corrected distributions over orbital eccentricity and inclination have not as yet been derived.

The relatively sharp cutoff in S/C ratio with distance implies great difficulties for any hypothesis involving formation of asteroids of various types in widely differing regions of the solar system and their subsequent relocation in the main belt. (That is not to say, of course, that some asteroids of rare type could not have such a history.) Also let me emphasize that Figure 2 does not represent a progressive darkening of asteroid surfaces with distance, but variations in the relative proportions of distinct types. The situation may have been misunderstood by Whipple (1977). Some tendency for S objects to have more neutral colors at greater distance has been noted (Zellner *et al.*, 1977c), but generally objects of a given type tend to show the same range of optical properties no matter where located.

### Distributions Over Diameter

Figure 3 illustrates the bias-corrected distributions of C and S+M Types as derived by Zellner and Bowell (1977). The data are consistent with parallel size-frequency relations, both showing a change of slope near 160 km; however, the statistics are poor for the smaller sizes and also for diameters  $>200$  km due to the small number of objects present. An alternate interpretation of the same size-frequency data is given by Chapman (1977).

### FAMILIES

Among the most exciting results of the past year is the evidence that the Hirayama families, consisting of asteroids with strongly clustered orbital elements, are not random collections of field objects but show a high degree of internal homogeneity (Hansen, 1977; Gradie and Zellner, 1977). The families apparently originated as the collision fragments of discrete parent bodies. Thus we can see into the interior of the parent bodies, including possibly differentiated objects, in ways not possible for the major planets and their satellites.

The better-populated families often have only one or two large members or consist entirely of small objects. Thus they were generally overlooked in the bright-asteroid surveys and are only now being explored by UVB and similar techniques. When comparing the compositions of the smaller family members with the non-family field population, we are dependent upon an incompletely-tested assumption, namely that the mixture of types seen for large asteroids is also characteristic of the field population at small sizes.

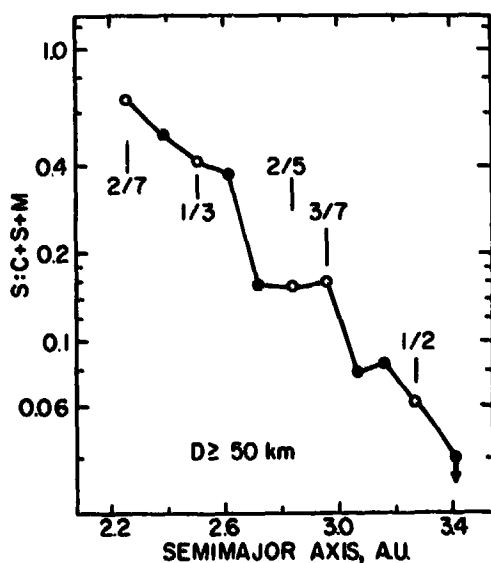


Fig. 2. Ratio of bias-corrected type frequencies, as a function of orbital semimajor axis. Open circles indicate zones containing major Kirkwood gaps. Adapted from Zellner and Bowell (1977).

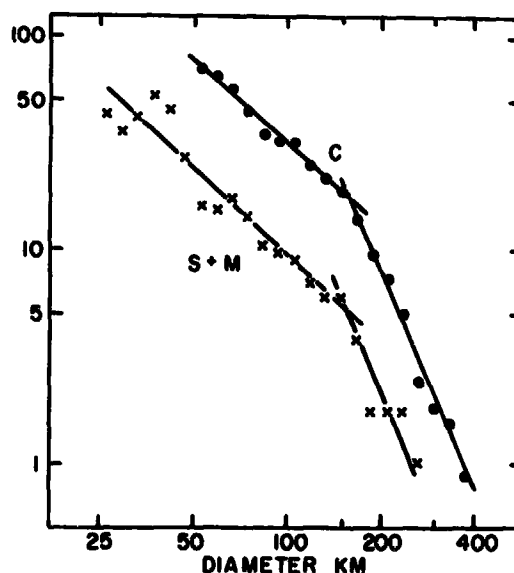


Fig. 3. Bias-corrected number of asteroids of Type C, and Types S plus M, in intervals of 0.05 in log diameter for the whole main belt. Adapted from Zellner and Bowell (1977).

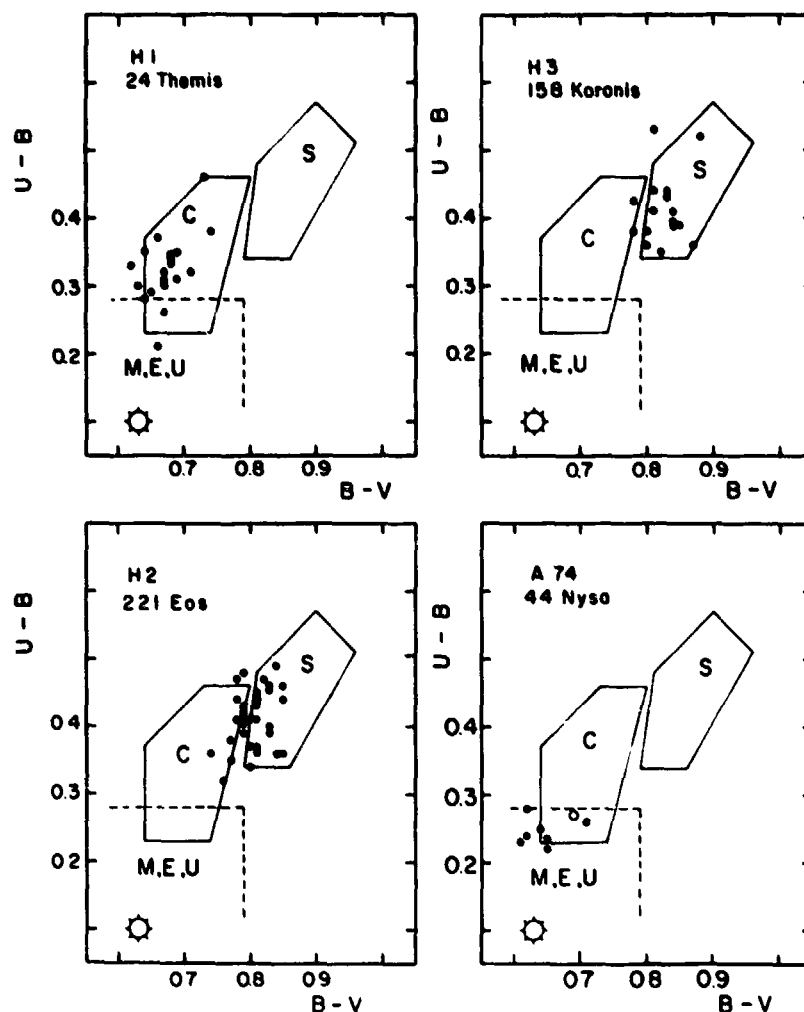


Fig. 4. Observed UBV colors for minor planets in the Hirayama families associated with 24 Themis, 158 Koronis, 221 Eos, and 44 Nysa. Color domains of the C, S, M, and E Types are as defined by *Bowell et al.* (1978). The symbol at  $B-V = 0.63$ ,  $U-B = 0.10$  indicates adopted colors of the Sun. The open circle in the Nysa family represents the M object 135 Hertha. Data are from the TRIAD file and from *Degewij et al.* (1978).

Figure 4 illustrates UBV data for four families. The family Arnold 74 is located in the inner regions of the main belt but seems to contain no typical C or S asteroids at all. It consists of the irregularly-shaped 80 km E object 44 Nysa, the 80 km M object 135 Hertha, and at least six small fragments of an unidentified but unusual compositional type.

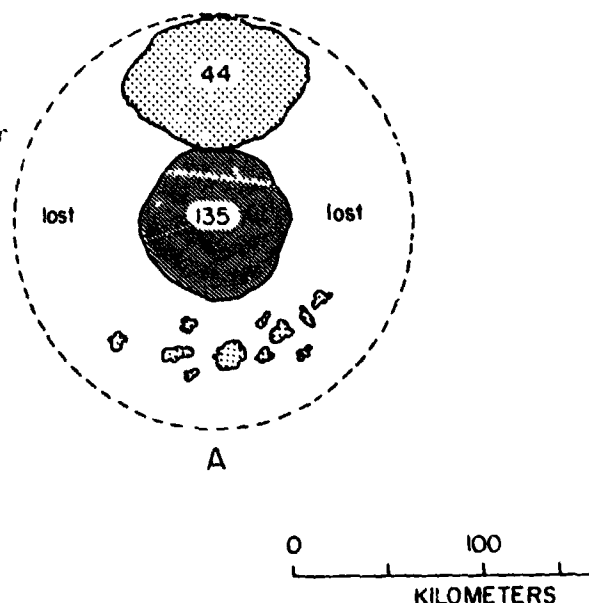
Zellner *et al.* (1977b) attempted to reconstruct this family as in Figure 5, with the hypothesis that the small fragments are also of the E type and that, together with 44 Nysa, they represent the enstatite-achondritic shell collisionally spalled from the iron core 135 Hertha. Alternate interpretations are possible, as for example a forsterite mineralogy for the E objects, or an enstatite-chondritic nature for Hertha and some of the small fragments. Meteoritic evidence tends to favor a common origin for the enstatite chondrites and achondrites (Clayton *et al.*, 1976; Hertogen *et al.*, 1978). In any case a very interesting parent body has been broken open to form the 44 Nysa family.

The families Hirayama 2 (221 Eos) and Hirayama 3 (158 Koronis) are the subject of a survey in progress by UVB and thermal-radiometric techniques (Gradie *et al.*, 1977). The Koronis objects appear to be entirely of Type S, although the field population consists of at least 80% Type C at its heliocentric distance. This family (as does Hirayama 2) has no prominent largest member but at least a dozen objects in the 30-50 km size range, and is clearly the result of a catastrophic fragmentation event. Here we have evidence that S objects are internally homogeneous with no large iron core or other marked compositional inhomogeneity.

The 221 Eos family is similarly distinct from the field population and contains the only known asteroids which appear to be intermediate between C and S types. Preliminary indications are that they in fact form a linear series between typical C and S properties in both albedo and color. A reflection spectrum of 221 Eos itself (McCord and Chapman, 1975) is peculiar and has been interpreted in terms of a mixture of mafic silicates and opaques perhaps resembling the C3 chondrites (Gaffey and McCord, 1977). Further speculations on the nature of this family would be premature.

In UVB colors the 24 Themis family (Hirayama 1) appears to consist entirely of C objects, six of them falling in the 100-200 km diameter range. Here we have a background problem, since the field population at semimajor axis 3.14 AU is at least 90% of Type C. Still the chances are small that no S or other types would be found out of 19 objects sampled, and this family also appears to have a collisional origin.

Fig. 5. Reconstruction of the 44 Nysa family, as suggested by Zellner *et al.* (1977b). 135 Hertha is taken to represent a metallic core, and 44 Nysa and the smaller fragments a mantle of enstatite-achondritic (or other transition-metal-free) material.



It has several times been suggested that C asteroids may consist of S type or other stony-metallic cores which subsequently accreted surface layers of dark carbonaceous material. This hypothesis may be attacked on several grounds, one of which is the evidence from the families. For the Koronis object it would be necessary to assume that the C material was entirely removed before the major collision that produced the family, or else disposed of in some way. For the Themis family the putative core would have to be still concealed in one of the larger members.

Finally, let me note that at least half the asteroid population cannot be assigned to recognizable family groups, but may nevertheless have originated in collisions for which the debris is now widely dispersed. Thus the overall complexion of the belt, including such general trends as seen in Figure 2, may be telling us more about the individual properties of a rather small number of parent bodies than about the continuum properties of the solar nebula.

#### THE OUTLIERS

Of the 2045 presently numbered minor planets, 1917 move in orbits with semimajor axis between 2.06 and 3.65 AU, eccentricity  $<0.35$ , and inclination  $<30^\circ$ . Of the remainder, there are 21 numbered Trojans near the equilateral Lagrangian points of Jupiter, 27 Hildas near the 2/3 resonance at 3.95 AU, 16 Hungarias with relatively high inclination orbits inside the 1/4 resonance, and 48 Apollo/Amor objects in Mars- or Earth-crossing orbits (see Figure 1). The sampling is clearly much biased in favor of nearby objects. Sixteen numbered asteroids, including 2 Pallas with its exceptional inclination, fall into none of the above categories. The Hungarias, Hildas, and Trojans may have been formed at their present distances, but the Apollos and Amors appear to need a source of replenishment from the main belt or from the comet population (Wetherill, 1976, 1978).

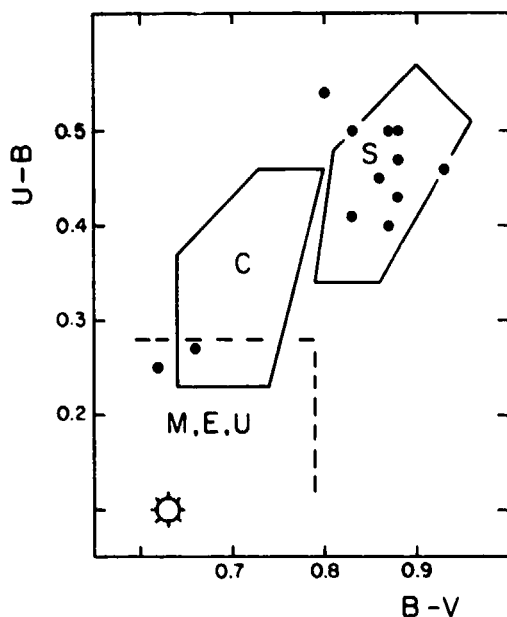


Fig. 6. UBV colors for twelve asteroids in Earth- and Mars-crossing orbits. Data are from the TRIAD file.

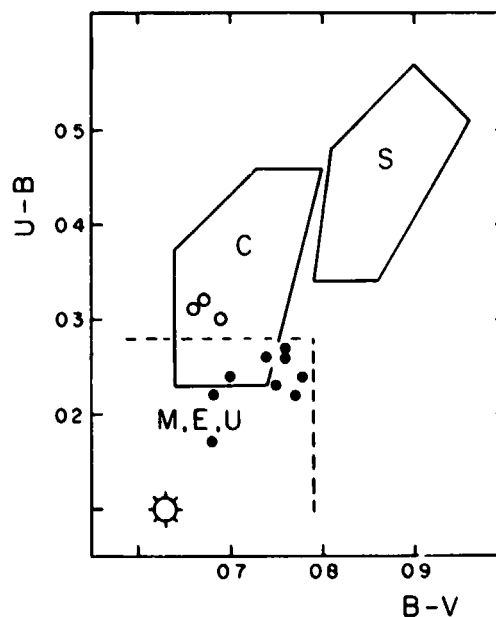


Fig. 7. UBV colors for nine Trojan asteroids (filled circles) and for the outer satellites JVI, JVII, and Phoebe. Data are from Degewij *et al.* (1978) and unpublished results at the University of Arizona.

Figure 6 illustrates UVB data for a dozen small bodies in Earth- and Mars-crossing orbits. Mostly they have S-like optical properties, but bias corrections are difficult. (Actually the distribution of types is very similar to that for the dozen brightest main belt asteroids.) Some of these have been studied in detail, and 433 Eros is perhaps the best-observed of minor planets (*Icarus*, Volume 28, No. 1, 1976). Object 1685 Toro is the best identified candidate for an ordinary-chondritic composition among the asteroids (Chapman *et al.*, 1973). Object 1580 Betulia is the only well-established C type among the Mars-crossers; 1474 Beira has relatively neutral colors of unknown significance.

Figure 7 displays UVB colors for nine Trojans. McCord and Chapman (1975) reported exceptional reflection spectra turning upward in the infrared, unlike anything in the main belt, for the Trojans 624 Hektor and 911 Agamemnon. The available UVB colors and uniformly low thermal-radiometric albedos (Cruikshank, 1977; Degewij *et al.*, 1978) argue a high degree of homogeneity among the Trojans, with an unidentified composition distinct from the rest of the asteroids. Figure 7 also illustrates remarkably similar colors, distinct from the Trojans, for the outer satellites JVI, JVII, and Phoebe.

The Hilda asteroids are poorly explored. UVB colors reported by Degewij *et al.* (1978) are generally Trojan-like, but with wider scatter. Degewij *et al.* find a variety of types among the Hungarias; 434 Hungaria itself is of the very rare E type.

#### FUTURE WORK

In spite of enormous progress in the last five years, we are only beginning to scratch the surface of the minor planet population with regard to some very interesting questions. Future space missions may be limited by the laws of celestial mechanics to objects which now seem wholly insignificant, and it is vital that we be able to make intelligent choices among such possible targets. Returns from the Infrared Astronomy Satellite will trivialize efforts to date in the art of asteroid thermal radiometry, but radiometry alone is not enough for mineralogical classification. The UVB technique is capable of reaching almost any numbered asteroid, but is also limited in diagnosticity.

Detectors now exist by which it is possible to obtain diagnostic spectral reflectivity data at wavelengths out to 0.10  $\mu\text{m}$  for quite faint objects. A thousand minor planets could be thus observed in three years' work, and I believe that such a dedicated ground-based survey is the critical next step.

#### ACKNOWLEDGMENTS

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#### DISCUSSION

CHAPMAN: You have looked at several of the most populous families. Previously published data on representatives of other families have shown that they have heterogeneous compositions among the members, so it is not a general rule that asteroid families have members with identical compositions. There are other cases where there are considerable differences.

ZELLNER: We should look at those too.